Boundary Current and Mixing Processes in The High Latitude Oceans

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LONG-TERM GOALS

This project's overarching goal is to quantitatively expand our understanding of turbulent mixing processes in high latitude regions of the global ocean. It focuses on high latitudes because: (1) they are primary sites for surface conditioning of deep waters that drive the meridional overturning circulation, a primary component of the mean global ocean circulation, and one that relies on a balance between mixing and other processes; (2) they provide excellent, and in some cases extreme, examples of mixing-related phenomena that are active throughout the world oceans and therefore can broaden our parameter spectrum related to such phenomena; (3) they provide high quality, geophysical scale natural laboratories for field study of these phenomena because of a surface ice cover that stabilizes observation platforms; and (4) these remote areas are data-poor in comparison with the rest of the ocean, despite the importance of quantifying mixing processes and better understanding them within a global context.

OBJECTIVES

Work towards this goal is guided by the following objectives:

- Document deep, high latitude boundary currents and dense outflows, measure the associated mixing processes, and assess the impacts of these processes on water mass modification;
- Document and quantify the generation at high latitude ocean boundaries of mixing-related, small-scale features such as tidally-driven internal waves and intrusive interleaving, and assess their dynamics and impact on adjacent basin waters;
- Acquire quantitative, field-based information on seawater equation-of-state processes, such as double-diffusion, cabelling and thermobaric instability, that are anticipated to play significant roles at high latitudes where temperatures are low and static stability is frequently weak; and,
- Actively coordinate, through participation in working groups and conferences, results from these efforts with those being obtained through field efforts elsewhere in the global ocean and with parallel modeling efforts.

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APPROACH

This research is based primarily on collection and analyses of field data. Measurements are made using conductivity-temperature-depth profiling (CTD) systems, lowered and vessel-mounted acoustic Doppler current profiler (ADCP) systems, and microstructure profilers. Available microstructure profilers include a CTD-mounted scalar microstructure profiling system (CMiPS) and a free-falling, tethered vertical scalar and shear microstructure profiler (VMP). Ancillary data are acquired, in some cases, from moored instruments. The instruments are deployed from research platforms available under the auspices of programs funded by various US and foreign organizations, allowing access to resources that would otherwise be either unavailable or prohibitively costly. Study sites have been selected based on the likely occurrence of processes of interest, such as deep-water formation or modification and intense mixing associated with tidal or topographically controlled currents. Examples of such processes include dense outflows exiting the Ross and Weddell seas, intrusive interleaving that occurs along much of the Antarctic margin, and equation-of-state related phenomena (cabbeling and thermobaricity) that dominate the very weakly stratified Maud Rise region of the Weddell Sea.

Quantitative information on mixing is derived from field data using documented methods. For example the Thorpe displacement method is applied, under appropriate conditions, to high quality finestructure data derived from CTD casts [*Thorpe*, 1977; *Dillon*, 1982; *Galbraith and Kelley*, 1996, and others]. This method yields estimates of turbulent parameters such as dissipation and vertical eddy viscosity in waters having stable density stratification and vertical shear. The techniques derived by *Osborn and Cox* [1972] and *Osborn* [1980] are used as the basis for deriving mixing-related parameters from scalar and shear microstructure data. Vertical current profiles measured by vessel-mounted or lowered ADCPs have been used in conjunction with CTD data to estimate mixing under certain conditions [*Polzin et al.*, 2002]. We apply diverse methods under different physical situations, and the results are intercompared where possible in order to investigate the limitations of each method under conditions varying from extremely quiescent (e.g., double-diffusive) to very energetic (e.g., dense outflow with shear-driven instabilities) conditions.

Research carried out under this project is intrinsically collaborative because of its reliance on other programs for field platforms and instrumentation used for data collection. Laurence Padman (Earth & Space Research) has been the primary collaborator. Other collaborators include Arnold Gordon (Columbia University), Alejandro Orsi (Texas A&M Univ.) and Miles McPhee (McPhee Research).

WORK COMPLETED

This, the fourth project year, started directly upon return from a two-month deployment in the eastern Weddell Sea. Subsequent efforts have concentrated on processing and analyzing field data obtained through participation in this and other related projects as listed below. Specific accomplishments include:

- Continued as chair of IAPSO/SCOR Working Group 121 on Ocean Mixing, oversaw publication of conference proceedings from the IAPSO/SCOR Conference on Ocean Mixing [*IAPSO/SCOR Working Group 121 on Ocean Mixing*, 2006] within a special Ocean Mixing issue of *Deep-Sea Research 2* [*Muench et al.*, 2006a], and participated in organizing and chairing ocean mixing sessions at the 2006 AGU Ocean Sciences and Fall 2006 AGU meetings.

- Concluded, with publication of a co-authored paper on tidal conversion over the South Scotia Ridge, a multi-year effort to assess mixing-induced water mass modification in that region [*Padman et al.*, 2006a].

- Concluded, with publication of a co-authored paper, this project's participation in analyzing shelf-basin exchange via mesoscale processes in the western Arctic Ocean [*Kadko and Muench*, 2005].

- Participated in research leading to co-authorship of a submitted field/modeling-based manuscript describing dynamic interactions among the topography of the Maud Rise region of the eastern Weddell Sea, mean large-scale circulation, and mesoscale features that serve to precondition the region for strong diapycnal mixing and deep overturning [*de Steur et al.*, 2007.], results accepted for presentation at the Fall 2006 AGU Meeting [*de Steur et al.*, 2006].

- Led preparation of, and submitted for publication, a field-based manuscript describing diapycnal mixing conditions on the southwestern Antarctic Peninsula continental shelf, a seasonally ice-covered, relatively low energy regime [*Muench et al.*, 2007].

- Completed preliminary processing and analyses of microstructure data obtained during an austral winter cruise to the eastern Weddell Sea and presented preliminary results at the February 2006 AGU Ocean Sciences Meeting [*Padman et al.*, 2006b].

- Completed preliminary processing and analyses of intrusion and polynya dynamics data obtained during a 2004 cruise to the 142˚-154˚E sector of the Antarctic shelf-slope, presented early results at the 2006 AGU Ocean Sciences meeting [*Muench and Padman*, 2006], and further results accepted for presentation at the Fall 2006 AGU meeting [*Padman et al.*, 2006c; *Muench et al.*, 2006b].

- Completed derivation of diapycnal mixing parameters using the 2004 ISPOL western Weddell Sea field data. Results were presented at a project workshop during early 2006 and are being incorporated into a manuscript currently in preparation by multiple authors.

RESULTS

Observations obtained in 2003 from a well- developed cold, dense outflow from Drygalski Trough, situated on the northwestern Ross Sea shelf, document the process by which cold, dense shelf water mixes with warm Upper Circumpolar Deep Water to form a primary component of Antarctic Bottom Water (Figure 1). From the viewpoint of dense outflow physics, these observations provide an example of the extreme conditions that can be associated with a high energy outflow. Sampled on the steep upper continental slope, the flow extended from ~ 609 m down to the seafloor and consisted of two layers, each ~150 m thick, having different origins on the broad shelf to the south. Maximum downslope speed approached 1 m s-1. Scalar microstructure data reveal a vertical *T* gradient atop the flow (right-hand panel in Figure 1), of nearly 1˚C in 10 cm. The corresponding interfacial Froude number *Fr* was > 1, reflecting highly turbulent flow. The vertical eddy diffusivity, computed from microstructure, was *Kz* ≈ 0.004 m2 s-1, with a corresponding downward heat flux *Fh* ≈ 103 W m-2. Downstream gradients of *T* and *S* imply an interfacial entrainment rate *we* of ~ 400 m day-1 along the ~ 45 km pathway along which the flow was identifiable, the high rate being consistent with a high *Fr*. Entrainment rates derived using Thorpe-scale and scalar microstructure based methods were both ~100 m day-1, a factor of 4 less than computed from *T-S* properties but still large. These highly energetic density flows are impacted by tidal currents that can approach 1.5 ms-1 at the shelf break during spring tides. At such times, tidal currents significantly increase the mean benthic stress opposing the outflow and, consequently, the cross-stream (~ downslope) Ekman drainage flux [*Muench and Padman*, 2006].

Data from two additional shipboard deployments to the northwestern Ross Sea slope-shelf region, and coincident multi-year moored current, *T* and *S* observations, are being analyzed to broaden the geographical scope of the above summarized results and to assess seasonal variability. Acquisition during these deployments of shear microstructure data will increase our confidence in estimates of diapycnal mixing rates.

Dense outflows, with their associated mixing between cold, dense shelf waters and warmer UCDW, provide a primary mechanism for generation of AABW. Other mechanisms that contribute to water mass preconditioning prior to AABW formation include intrusion-driven mixing. While not as spectacular as the Ross Sea dense outflow, intrusions are common along most of the Antarctic shelf break, and so may play a significant role in the interactions among shelf and deep waters. The best recent examples we have are from a time series acquired offshore from the Mertz Glacier Tongue near 142˚-154˚ E. Representative profiles of *T*, *S* and dissipation ε (derived from shear microstructure) illustrate the nature of the intrusions (Figure 2). Significant intrusive activity was present below

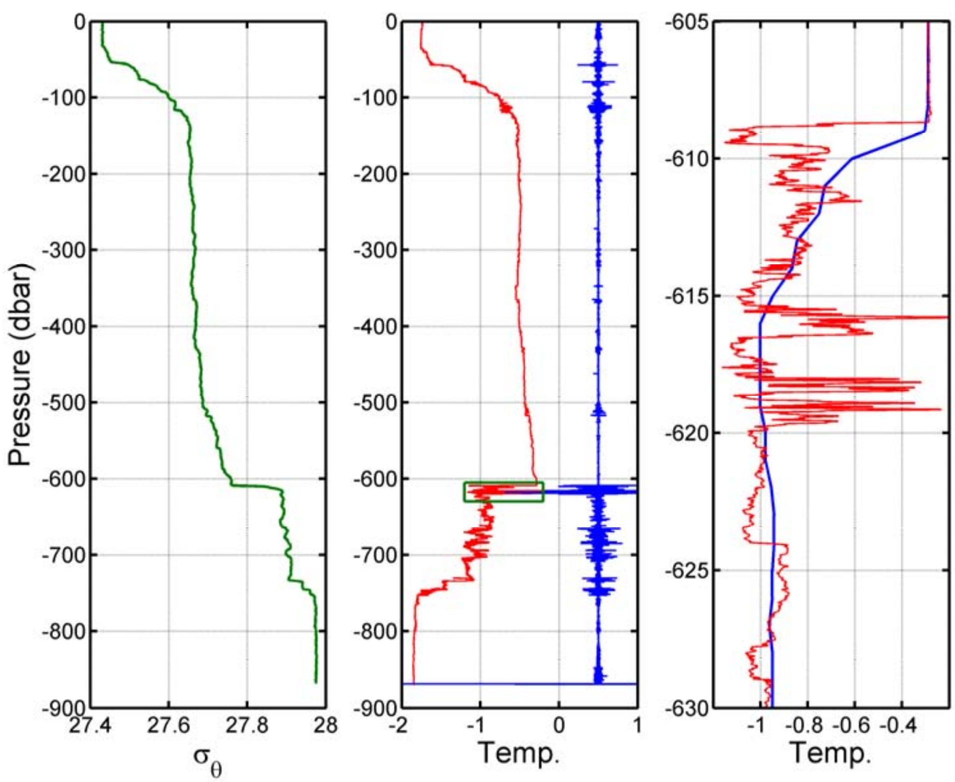

Figure 1. Sample vertical profile showing potential density σθ and T microstructure (as T and dT/dP) from a dense outflow exiting the northwestern Ross Sea.. Right-hand panel is an expanded profile showing T structure through the interface (corresponding to the green rectangle on the center panel) [Muench and Padman, 2006].

about 300 m, where warm water derived from UCDW is interleaving with cold shelf water [*Muench and Padman*, 2006; *Padman et al.*, 2006c]. The rate of mixing will help determine how sharp the shelf/slope front is, thus also how well insulated the shelf water is from the offshore warm water. Shear-derived ε indicates significant turbulence in the well-mixed benthic boundary layer from ~ 410 m to the seafloor. The steplike T and S shown in the enlarged panel, and corresponding weak peaks in ε, were consistent with double diffusion. Thermal microstructure (not shown) indicated that significant mixing was occurring across the intrusive boundaries. Double diffusion is believed to be a significant contributor to mixing associated with intrusions. Ongoing work will investigate the relative importance of these processes in diapycnal exchange and water mass modification related to intrusive interleaving.

Dense water is not produced at all sites surrounding Antarctica, and the Marguerite Bay region on the southwestern Antarctic Peninsula is one of many such exceptions. Of interest because of unusually high biological productivity, this deep and topographically complex shelf region is swept by intermittent subsurface intrusions of warm UCDW that originate from the Antarctic Circumpolar Current and provide heat and nutrients to the colder, biologically active upper ocean. Scalar microstructure, CTD and current data were acquired in 2002 in collaboration with the Southern Ocean GLOBEC program, and have been used to derive mixing estimates in order to test the hypothesis that diapycnal mixing provides the primary mechanism for transport of heat and dissolved materials from the subsurface layers to the biologically active upper ocean. Resulting diapycnal mixing coefficients K_z were an order of magnitude too small to provide upward transports sufficient to match the hypothesis. This result, reported in *Muench et al.* [2007] has served as a stimulus for investigation of other processes, such as topographically-driven or coastal upwelling, that might contribute to upward transports. It is worth noting that inclusion in this program of a field component addressing diapycnal mixing has proved crucial for testing the primary physical hypothesis for the high regional biological productivity in the Marguerite Bay region.

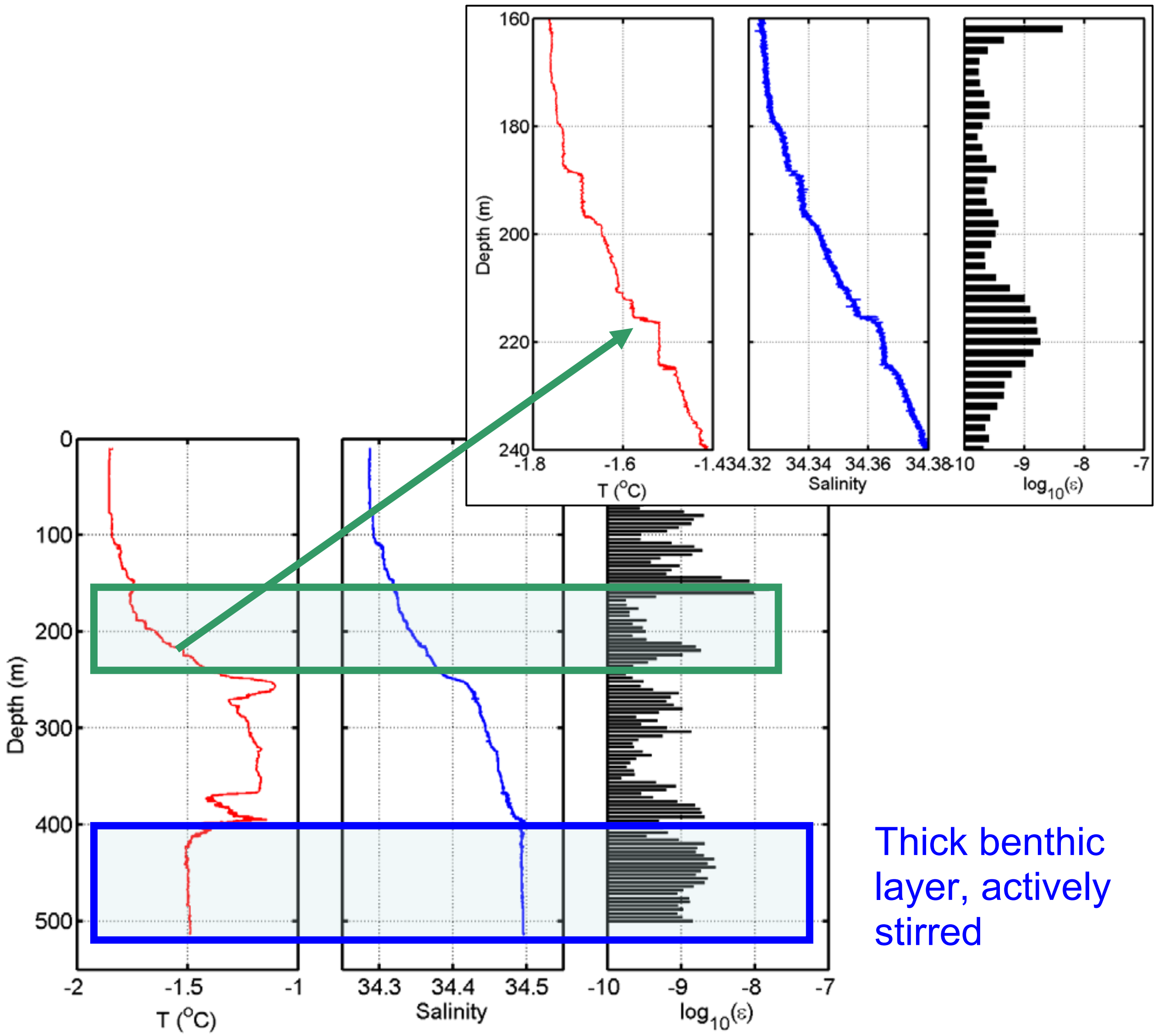

Figure 2. Vertical profiles of T, S and ε (from shear microstructure) over the Antarctic shelf break near 142-154˚E [Muench and Padman, 2006]. Upper panel shows an enlargement of the upper gradient region defining the warm intrusion. Green rectangle encompasses double diffusive strata, and blue rectangle encompasses a turbulent bottom boundary layer.

Considerably farther east, the region immediately surrounding Maud Rise Seamount in the eastern Weddell Sea is overlain in winter by pack ice that is perennially thinner than over the surrounding ocean and is, at times, completely absent. Field data obtained from the region during the 2005 MaudNESS program revealed a mid-depth warm annulus surrounding the Rise and overlain by a greatly reduced mixed layer depth. Possible relationships among this mesoscale feature, greatly weakened vertical stratification surrounding the Rise, and enhanced diapycnal mixing are being investigated. An integrated mesoscale field and modeling effort has shown that presence of the warm annulus and associated shoaling depends upon impingement of the regional southwestward flow onto the Rise [*de Steur et al.*, 2006; 2007]. Warm water comprising the halo originates as Upper Circumpolar Deep Water that flows southwestward into the eastern Weddell Sea. Impinging on the Rise, which is overlain by a Taylor column, this flow bifurcates with the majority flowing westward along the northern flank. Cyclonic and anticyclonic eddies form during this flow past the Rise, then continue westward after separating from the flanks of the Rise. The eddies are dominated by cyclones, which adhere to the Rise more strongly than anticyclones. Model results predict, and satellite altimetry data show, formation of 3-5 eddies per year through this mechanism. Averaged over time, presence of the eddies accounts for the halo and its accompanying shoaled pycnocline. In the case of an extremely strong pulse in the southwestward regional flow, the model predicts that the halo becomes more intense and widespread.

This apparently stable and quasi-steady mesoscale feature overlying Maud Rise has significant consequences for diapycnal mixing in the region and, since vertical ocean heat fluxes are involved, for the overlying pack ice cover. Stratification, which is weakened in the vicinity of Maud Rise by passage of the warm eddies, is consistent with a diapycnal cabbeling control over mixing between the surface mixed layer and the warmer deep water [*Padman et al.*, 2006b]. Winter pack ice can form, releasing brine to the surface layer, until the cabbeling limit is approached. At that time double-diffusive-like steps form, upward heat flux increases and warms the surface mixed layer. This in turns melts ice, reduces salinity and moves the system away from the cabbeling limit. Preliminary results based on scalar and shear microstructure profiles show small step-like features that are consistent with occurrence of cabbeling. Ongoing analyses address the interactions among cabbeling, double-diffusion and shear-driven turbulence in this complex system.

IMPACT/APPLICATIONS

The research reported here has potential impact and application for parameterization of mixing in large-scale ocean models, for assessing the dynamics of interactions among mixing and the mesoscale, and for expanding our limited present information base for the ocean-wide distribution of mixing. The research emphases derive in part from, and therefore reflect, recommendations recently published by the IAPSO/SCOR Working Group 121 on Ocean Mixing [*IAPSO/SCOR Working Group on Ocean Mixing, 2006*].

Quantitative and dynamic understanding of ocean mixing processes lags that of the large-scale circulation. This gap in understanding has contributed to an inability of large-scale numerical models to properly parameterize small-scale processes that involve mixing. This failing has in turn limited the ability of models to accurately recreate all aspects of the large-scale ocean circulation or, by extension, to credibly predict potential changes. Nowhere is this problem more evident than in high latitude regions where surface waters are densified and sink to form primary components of the global MOC. The research reported here contributes a significant proportion of the quantitative information currently available concerning turbulent mixing processes on the Antarctic shelf-slope regions - the Ross and Weddell seas, and the Adèlie Coast – responsible for production of virtually all Antarctic Bottom Water. These processes have a primary impact on the formation rates and physical characteristics of dense water that forms around the Antarctic margins, descends to form the southernmost link in the MOC, and provides the primary component for Antarctic Bottom Water that underlies most of the global ocean.

This research involves assessment of mixing parameters using a variety of methods including CTD-derived finestructure profiles, scalar and shear microstructure profiles, and vertical current profiles. Intercomparison of these methods and of the conditions under which each is appropriate, coupled with attempts to develop user-friendly methods, are part of an ongoing attempt to entrain interested nonspecialists into the "ocean mixing" community. The hope is that this would enhance acquisition of mixing data sufficiently to, over time, construct a global scale "ocean mixing climatology".

RELATED PROJECTS

The following closely-related projects have contributed data for use in the research reported here. Unless noted otherwise, funding for research platforms and instrumentation has been provided by the NSF.

The Antarctic Slope study (AnSlope) (http://www.ldeo.columbia.edu/physocean/anslope) seeks to assess slope processes and their impacts on local water modification, cross-shelf transport and on the dense outflow from the Ross Sea. Underway analyses attempt to quantify and learn the dynamic processes responsible for regional diapycnal mixing, and the impact of this mixing on larger-scale processes.

The Maud Rise Nonlinear Equation of State Study (MaudNESS) (http://fish.cims.nyu.edu/project_maudness/overview.html) seeks to quantify and to better constrain, through analyses of small-scale and microstructure observations in the very weakly stratified eastern Weddell Sea, seawater equation of state-related processes such as cabelling, double diffusion and thermobaric effects.

Ice Station Polarstern (ISPOL) (http://www.ispol.de) was a late winter cruise to the western Weddell Sea that allowed acquisition of CTD, ADCP and scalar microstructure data adequate to assess the deep northward density flow and to compare overflow and the mixing environment with those observed in 1992. Field expenses were borne by the Alfred-Wegener-Institute for Polar and Marine Research, Bremerhaven, Germany.

Southern Ocean GLOBEC (http://www.ccpo.odu.edu/Research/globec_menu.html) addresses processes on the deep, broad continental shelf of the southwestern Antarctic Peninsula. Analyses of high quality CTD, ADCP and scalar microstructure data acquired during multiple cruises to the region provide raw material for assessment, essential to modeling the regional circulation, of diapycnal mixing.

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